**Fermilab**

# Particle Physics Division
# Mechanical Department Engineering Note

Number: MD-ENG- 243 Date: April 27, 2010

Project Internal Reference:

Project: DECam

Title: The Mechanical Behavior of the Simulator Rotator Lifts Four Rings Together Horizontally Under Three Lifting Points.

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Reviewer(s): 5/11/10

Key Words: Simulator, Rotator, Outer Race frame, Dead load, Live Load, Allowable Stress, Computed Stress, FEA, Reaction, Deflection, Lifting.

Abstract Summary:

The mechanical behavior of the DECam Simulator Rotator race frame(s) under three lifting points with 35,000 total load were extensively discussed, calculated, analyzed and studied through the mathematical computation and FEA method respectively. The results from both approaches are consistent with each other and meet the subject applicable codes.

Applicable Codes:

"Allowable Stress Design", AISC, 9th edition
"Aluminum Design manual", 6th edition, By the Aluminum Association.
"Fastener Standards" 6th edition, by Industrial Fasteners Institute", 1988
"Steel Structures" by C. Salmon & J. Johnson, 3rd edition
"Below the Hook Lifting Devices" ASME B30.20

# Structural Analysis and Calculations for Simulator Rotator Race Frames to Lift Four (4) Rings Together Under Three Lifting Points

***Background Brief Introduction***:

The DECam Telescope simulator is composed mainly by Rotator (composed by Inner Race and Outer Race) and the Telescope. The Simulator Rotator and the Inner and Upper rings of the Telescope will lift together through three (3) Outer Race lifting lugs as showing in Figure 1. The detail information, configuration and others of the DECam Simulator can find from the link: http://des-docdb.fnal.gov:8080/cgi-bin/RetrieveFile?docid=1528&version=3&filename=rotator1-simulator-des-022708.ppt

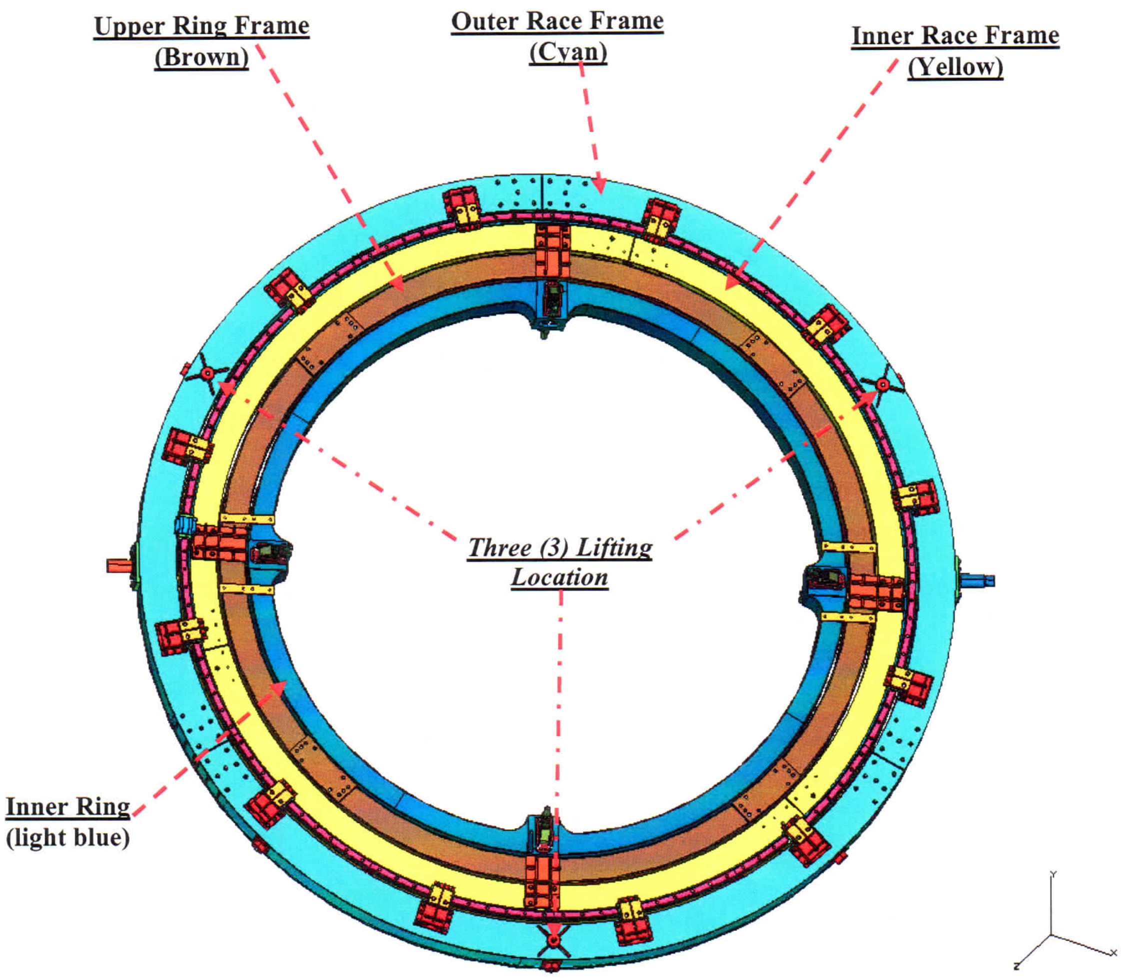



Figure 1, Isometric view of the telescope simulator Rotator, Inner Ring and Upper Ring

***Design Criteria, Introductions and Assumptions***:

$W_{rings}$ = 15,000 lbs (total mass weight of the Inner ring and Upper ring)
$W_{rotator}$ = 20,000 lbs (mass weight of the Inner race, Outer race and the others)
See dwg: ME-436983, MD-480079.
$W_{tl}$ = 35,000 lbs (total weight of the Inner ring, Upper ring and the Rotator).
where:
$W_{dlo}$ = 10,000 lbs (mass weight of the outer race), dead load.
$W_{dli}$ = 10,000 lbs (mass weight of the inner race), dead load
$W_{ll}$ = 15,000 lbs (combined wt. of the inner ring and upper ring), live load
Nominal dim. of the inner race: 215" ($d_i$) x 239" ($d_o$) x 12.0"
Nominal dim. of the outer race: 241" ($d_i$) x 265" ($d_o$) x 12.0"

***The Material Properties and the Allowable Stresses***:

Material of the Rotator race frame (See drawings ME-436905, ME-436945 and ME-436947): ASTM A36

$F_u$ = 58 ksi,
$F_y$ = 36 ksi
$F_{b1} = 0.6\ F_y$ = 21.6 ksi (Allowable bending stress per "ASM")
$F_{v1} = 0.4\ Fy$ = 14.4 ksi (Allowable shear stress per "ASM")
$F_{b2} = F_{v2} = F_y / 3$ = 12 ksi (Allowable tensile and shear stress per "Below the Hook Lifting Devices", pick the lesser value as the final allowable stresses:

**$F_b = F_{b2}$ = 12.00 ksi**
**$F_v = F_{v1}$ = 12.00 ksi**

**<u>Under the case of three (3) lifting points from the Outer race frame</u>**

***Simulating the Loading Case, Define the Boundary Condition and Find Out the Geometrical Properties:***

When four rings are lifted together by 3 points through the hoist rings and lifting lugs horizontally as shown from figure 1 on page 2, we can assume that the Outer Race frame acting as a continuous beam of three (3) equal spans with uniformly distributed load and torsional moment, the distributed load is total load (the dead load of the outer race frame) plus the live load of the inner race frame, inner ring and upper ring) divided by the circumferential length of the outer race frame. We'll discuss the torsional moment in details from page 6 to page 8.

The force distribution is illustrated in Figure 2 of page 4, where two of the three lifting lugs represented by location B and C, the third lifting lug represented by location A and D together to become a closed circle continuous beam.

where:

$r_c$ = ((265" +241")/2) ÷ 2 = 126.50"

The mean radius of the outer race frame in radial direction.

$L_{120}$ = (120/360) x 2 π $r_c$ = 264.94"

The circumferential length of frame respect to 120 degree segment & mean radius.

w = $W_{t1}$ ÷ 3 $L_{120}$ = 44.04 lbs/in

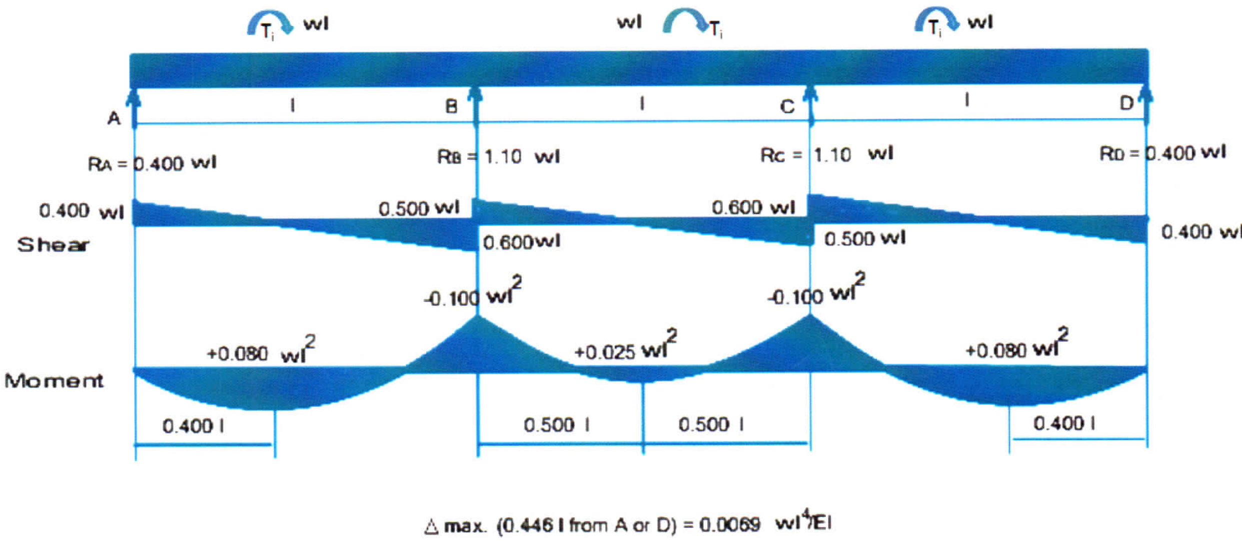



Figure 2, Continuous beam of three equal spans with uniformly distributed load & Torsional Moment (See case 42, VII-127, "Aluminum Design Manual", 6th edition)

It is found that the max. moment and the max. Shear force is at the lifting lug location (location B or C):

$M_{max}$ = 0.100 w $L_{120}^2$ = 0.100 x 44.04 lbs/in x 264.94$^2$ in$^2$
= 309,131 lbs –in

$V_{max1}$ = 0.600 w $L_{120}$ = 0.600 x 44.04 lbs/in x 264.94 in
= 7,001 lbs.

However, we conservatively assume that:

$V_{max}$ = $W_{t1}$ ÷ 3 = 35,000 lbs ÷ 3 = 11,667 lbs.

Since the max. moment and the max. shear force both locate in the lifting location, let's get the geometrical property of the lifting lug area of the Outer race frame:

The detail construction of the Outer race frame in the lifting lug location can be found from bottom view, section T-T and detail S of drawing ME-436905. For the sake of simple and conservative approach, the geometrical property we based on from Figure 3 (2) has omitted the lifting lug and the other reinforcing gussets as shown from figure 3 (1) of page 5.

It found out that the geometrical property of the Outer race frame as:

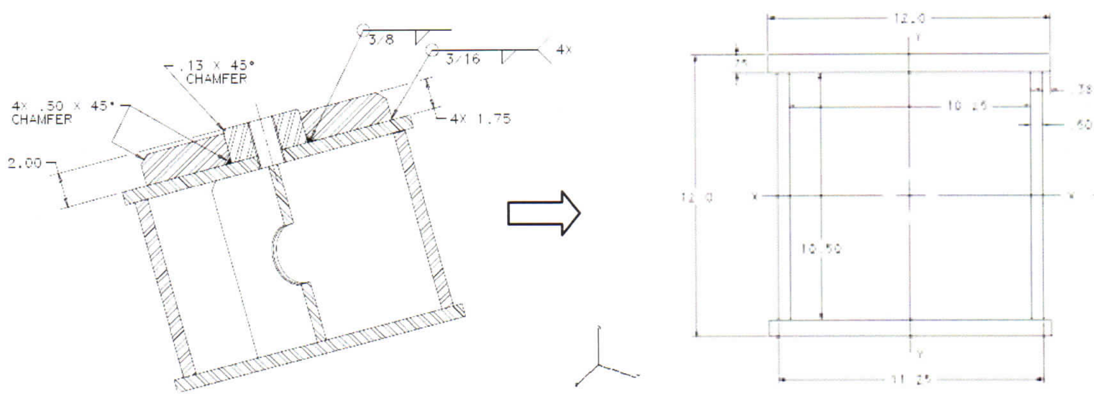
$I_{xx1} = [b\,(d^3 - d_1^{\,3})] \div 12$ (See page 6-19, ASD, 9th edition)
$\quad = 12 \times (12^3 - 10.50^3) \div 12\ in^4$
$\quad = 570.375\ in^4$
$A_1 = (0.75 \times 12.00 \times 2)\ in^2 = 18\ in^2$

$I_{xx2} = (0.5 \times 10.50^3 \times 2) \div 12\ \ in^4$
$\quad = 96.47\ in^4$
$A_2 = (0.50 \times 10.50 \times 2)\ in^2 = 10.50\ in^2$

Where : $b = 12$ in
$d = 12$ in
$d_1 = 10.50$ in
$C_{yy} = 6$ in

$I_{xx} = I_{xx1} + I_{xx2} = (570.375 + 96.47)\ in^4$
$\quad = 666.845\ in^4$
$S_{xx} = I_{xx} \div C = 111.14\ in^3$

$A = A_1 + A_2 = 28.50\ in^2$




(1) (2)

Figure 3, <u>The cross-sect view of the Outer race frame cut through the supt. location</u>

The radius of the gyration about the x axis:
$r_{xx} = 4.837$ in

Similar approach can find that:

$I_{yy1} = 10.50 \times (11.25^3 - 10.25^3) \div 12\ in^4$

$= 303.57 \text{ in}^4$
$I_{yy2} = (0.75 \text{ x } 12^3 \text{ x } 2) \div 12 \text{ in}^4$
$= 216 \text{ in}^4$

$I_{yy} = I_{yy1} + I_{yy2} = 519.57 \text{ in}^4$

$S_{yy} = 92.37 \text{ in}^3$
where $C_{xx} = 5.625$ in

The radius of the gyration about the y axis:
$r_{yy} = 4.27$ in

The polar moment of inertia about the z axis:
$J_{zz} = 1{,}186.415 \text{ in}^4$

The radius of the gyration about the z axis:
$r_{zz} = 6.452$ in

***<u>To find the maximum working computed stresses subject the defined boundary condition:</u>***

*To find the working computed stresses subject the defined boundary condition:*

$f_b = M_{max} \div S_{xx} = 309{,}131 \text{ lbs -in } \div 111.14 \text{ in}^3$
$= \underline{2.782 \text{ ksi}} < F_b = \underline{12.00 \text{ ksi}}$

$f_{v1} = V_{max} \div A = 11{,}667 \text{ lbs} \div 28.50 \text{ in}^2$
$= \underline{0.41 \text{ ksi}}$

***To find the maximum deflection under the boundary condition of three lifting lug:***

$\delta_{max} = 0.0069 \text{ w } L_{120}^4 / EI_{xx}$ (See figure 2 of page 4)
$= 0.0069 \text{ x } 44.04 \text{ lbs/in x } 264.94^4 \text{ in}^4 \div 30 \text{ x } 10^6 \text{ psi x } 666.845 \text{ in}^4$
$= 1{,}497{,}223{,}134 \text{ lbs-in}^3 \div 2.000535 \text{ x } 10^{10} \text{ lbs-in}^2$
$= \underline{0.07484 \text{ in}}$ (between two lifting lugs)

***<u>To find the torsional moments $T_i$:</u>***

We also assume that there are torsional moments applying to the beam support location (lifting location) since it is a circular beam with off center distance $e_i$.

So it is necessary to study the mechanical behavior of the Rotator under the torsional moment with eccentric distance $e_i$:

We <u>conservatively assumed</u> that all eccentric forces transferred to the Outer race frame, and all the torsional moments will be resisted by the Outer race frame only.

We assume that the maximum off center distance:

$e_{max} = [(265" + 241") \div 2] \div 2 = 126.50$ in = <u>OE</u>

$= r_c$ (See figure 4 of page 6)

Per page 2, it is found out that the dead weight of the Outer race is: $W_{dl} = 10{,}000$ lbs
This mass weight is uniformly distributed over the Outer race frame length of
$L = \pi D_m = \pi (d_o + d_i)/2 = 794.82"$

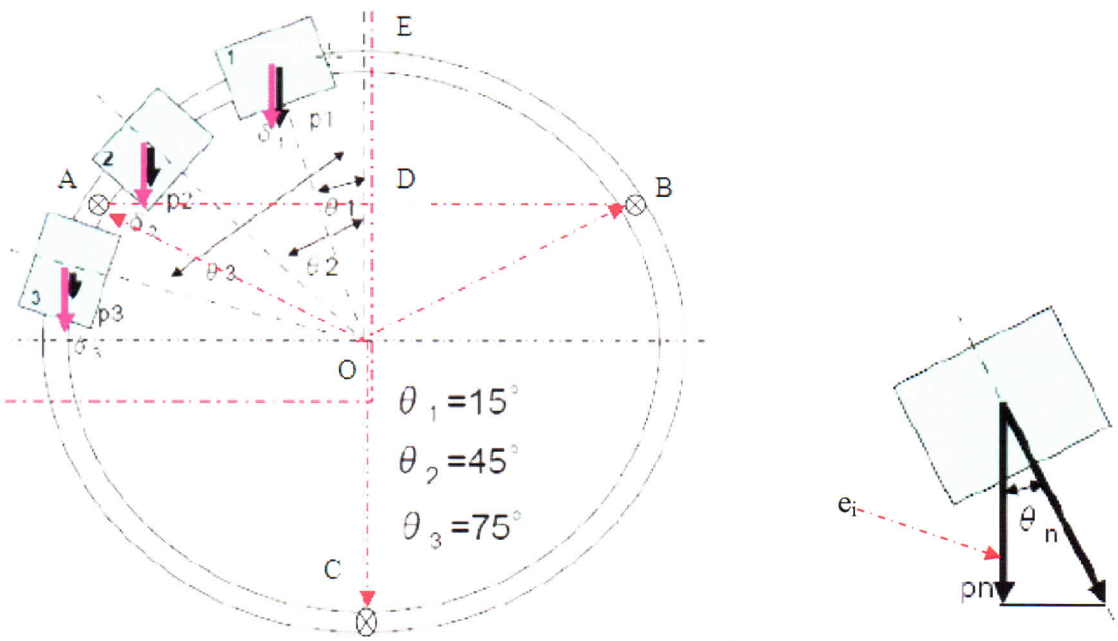



Figure 4, <u>The diagram of the bearing brackets of the Outer race frame (only showing quarter section).</u>

Location A, B, C of figure x represents the three lifting points of the Outer race frame. The uniform weight $w = W_{dl}/L = 12.5815$ lbs/in, the eccentric uniform load w (to xy plane) will uniformly distributed from location E to location A (the lifting location) as showing from figure 3.3. The torsional moment at the support will be:

$T_1 = w\,(\underline{ED})^2 \div 2 = \underline{25{,}167 \text{ lbs-in}}$

Where line <u>ED</u> = $\text{SIN}30^0$ x <u>OE</u> = 63.25"

The dead mass weight of the Inner race frame will transferred to the Outer race frame through 12 THK bearing blocks, each quarter section has 3 bearing blocks as it displayed from figure 3.3:

$T_2 = P_2\ \Sigma e_i$

Where: $P_2 = 10{,}000 \text{ lbs} \div 12 = 834 \text{ lbs}$.

The weight of the Inner race frame distributes to each THK bearing block.

$e_i$: The distance between the xy plane and the bearing block in z axis.

Where:

$e_1 = r_m\,(=e_{max})\ \text{COS}15^{\circ} - \underline{OD} = 126.50\text{”} \times 0.9659 - 63.25\text{”} = 58.9364\text{”}$

$e_2 = r_m\,(=e_{max})\ \text{COS}45^{\circ} - \underline{OD} = 126.50\text{”} \times 0.7071 - 63.25\text{”} = 26.1982\text{”}$

$T_2 = P_2\ \sum e_i = 834 \text{ lbs } (58.9364 + 26.1982) \text{ in}$

$= \underline{71{,}002 \text{ lbs-in}}$

$T_3 = P_3\ \sum e_i$

where $T_3$ is the torsional moment at the support location generated from the mass weight of the telescope $W_{tele} = 15{,}000$ lbs (See page 3).

$P_3 = 15{,}000 \text{ lbs} \div 12 = 1{,}250 \text{ lbs}$. /12 bearings

Per bearing

$T_3 = P_3\ \sum e_i = 1{,}250 \text{ lbs } (58.9364 + 26.1982) \text{ in}$

$= \underline{106{,}419 \text{ lbs-in}}$

$T_t = T_1 + T_2 + T_3$

$= (25{,}167 + 71{,}002 + 106{,}419) \text{ lbs-in}$

$= \underline{202{,}588 \text{ lbs-in}}$

$f_{v2} = (T_t\, r_{zz}) \div J_{zz} = (202{,}588 \text{ lbs-in} \times 6.452 \text{ in}) / 1{,}186.415 \text{ in}^4$

$= 1.102 \text{ ksi}$

$f_v = f_{v1} + f_{v2} = (0.41 + 1.102) \text{ ksi} = \underline{1.512 \text{ ksi}} < F_v = 12.00 \text{ ksi}$

To find the angular deflection $\Theta$ of the Outer race frame subject the torsional moment $T_t$:

$\Theta = (T_t\, L_{eff}) \div GJ_{zz}$

$= (202{,}588 \text{ lbs-in} \times 132.47 \text{ in}) \div (12\text{x}10^6 \text{ psi} \times 1{,}186.415 \text{ in}^4)$

$= 0.00189$ radian

where: $G = 12 \times 10^6$ psi, modulus of elasticity in shear of the steel

$L_{eff} = a = (60/360) \times 2\pi \times r_c = 132.47\text{”}$

*Conclusions of the manual mathematical approach*:

$M_{max} = 309{,}131$lbs -in (at the lifting lug location) (see page 4)

$V_{max} = W/3 = 11{,}667$ lbs (see page 4)

$T_t = 202{,}588$ lbs-in (see page 8)

$\Theta = 0.00189$ radian (see page 8)

$\delta_{max} = 0.07484\text{”}$ @ the center between the lifting lugs (see page 6)

$f_b = \underline{2.782 \text{ ksi}} < F_b = 12.00$ ksi (see page 6)

$f_v = \underline{1.512 \text{ ksi}} < F_v = 12.00$ ksi (see page 8)

**The computed working stresses are satisfactory subject to the applying load.**

***Welding calculations for the lifting lug:***

The configuration and dimensions can find from the figure 3, figure 5 and drawing ME-436905. There are reinforcing gussets (5.0 x1.75" x 0.5") and stud (4.50" dia x 2.00") additional to the base main plate. treating the welds as a line, it is found that: ( per page 276, table 5.18.1, part 6, "Steel Structures" by C. Salmon & J. Johnson, 3rd edition)

*The computed welding geometric properties of the stud (4.5" dia. x 2.00"):*

$r = 2.25$ inch, $h = 2.00"$
$L_w = 2\,\pi\, r = 14.14"$ length of the welds
$I_{xx2} = \pi\, r^3 = 35.78\ in^3$
$S_{xx2} = \pi\, r^2$
$= 15.90\ in^2$

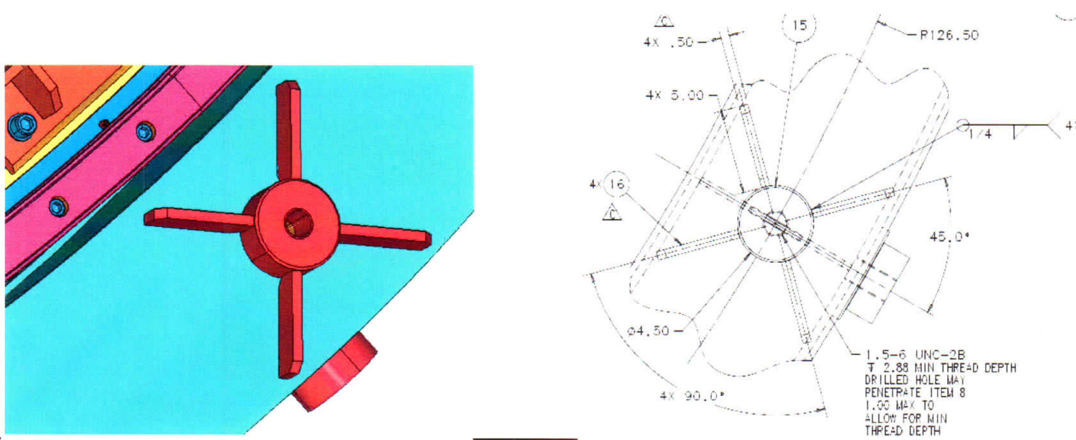



Figure 5. The configuration and dimension of the lifting lug weldment.

*The computerd working stresses subject to the applying load and the weld sizes:*

$f_v = V_{max} / L_{w1} = 11{,}667\ lbs / 14.14\ in$
$= 826\ lbs/in$

$C_l$ = combined working load per unit length÷ (effective factor × allowable Stress of the weld metal)
= (826 lbs/in) ÷ (0.707 x 21 ksi)
= **0.056 in** < 0.38 in (designated weld size in the area with consideration of the minimum size requirement of the fillet weld)
Where: $C_l$ is the size of the welds for the lifting lug connects with the main plate (3/4" thick).

**The designated weld sizes are satisfactory subject to the boundary condition.** (The calculation has not included the factor of reinforcing gussets for simple and conservative approach).

***To compute the pull out force from the base metal when using standard hoist ring (1½ -6, UNC-2B) subject the lifting lug design specification:***

There are two approaches to compute the pull out force $P_{out}$ from the base metal:

1. Per eq. 5.3.2.1-1, section 5.3.2.1, part I-A of "Aluminum Design Manual" 6th edition,

$$P_{out} = 0.85\, t_b\, D\, F_{tb}$$
$$= 0.85 \times 2.75 \text{ in} \times 1.50 \text{ in} \times 58 \text{ ksi}$$
$$= 203 \text{ kip (per lifting lug)} > 35 \text{ kip } (W_{t1}, \text{ a conservative assumption})$$

where: $t_b$ the thread engage length on base metal (see figures 3, 4 & 5).
D.the nominal dia. of the connecting hoist ring bolt
$F_{tb}$. The tensile strength of the base metal (ASTM A36).

2. Per A-9, "Fastener Standards" 6th edition, by Industrial Fasteners Institute", 1988

$$P_{out} = F_v * A_{ts}$$
$$= 12.0 \text{ ksi} \times \pi\, n\, L_e\, D_{smin} [\, 1/2n + 0.57735 (D_{smin} - E_{nmax})]$$
$$= 12.0 \text{ ksi} \times \pi \times 6 \times 2.75 \text{ in} \times 1.4976 \text{ in} \times [\, 1/12 + 0.57735 (1.4976 - 1.4022)\text{in}]$$
$$= 12.0 \text{ ksi} \times 77.63 \text{ in}^2 \times 0.1384$$
$$= 128.93 \text{ kip (per lifting lug)} > 35 \text{ kip } (W_{t1}, \text{ a conservative assumption})$$

where:

$A_{ts}$: Thread stripping area (shear area) of the internal thread
$= \pi\, n\, L_e\, D_{smin} [\, 1/2n + 0.57735 (D_{smin} - E_{nmax})$
$L_e$: length of the thread engagement
n: threads per inch
$D_{s\,min}$: Minimum major diameter of the external thread.
$E_{n\,max}$: Maximum pitch diameter of the internal thread.

**The designated internal thread (with the base material) are satisfactory subject to the applying load with 2 different analysis approaches.**

**FEA model and the Results for the Outer Race Frame Under Three Lifting Points:**

A FEA model also was built to simulate the boundary condition of the DECam Rotator Outer Race frame under three (3) point lifting case.
The FEA model frame from figure 6 of page 11 simulated the geometrical dimension and boundary condition as followings:

- Cross sectional dimension of the circular frame shown on figure 3 of page 5.
- Outside dia. of the Outer race frame: 265", inside dia. Of the frame: 241".

- Outside dia. of the Inner race frame: 239", inside dia. Of the frame: 215".
- Height of the frame: 12.00"
- Restraints the three lifting lugs.
- Total mass weight 15,000 lbs of the Inner ring and Upper ring applys to the Inner race frame through 4 connecting brackets as showing from figure 6.
- The total weight (frame dead load plus the external live load applying to the top plate of the frame) is 35,000 lbs (for whole model).
- Assumed the isotropic steel material of the Rotator race frames.

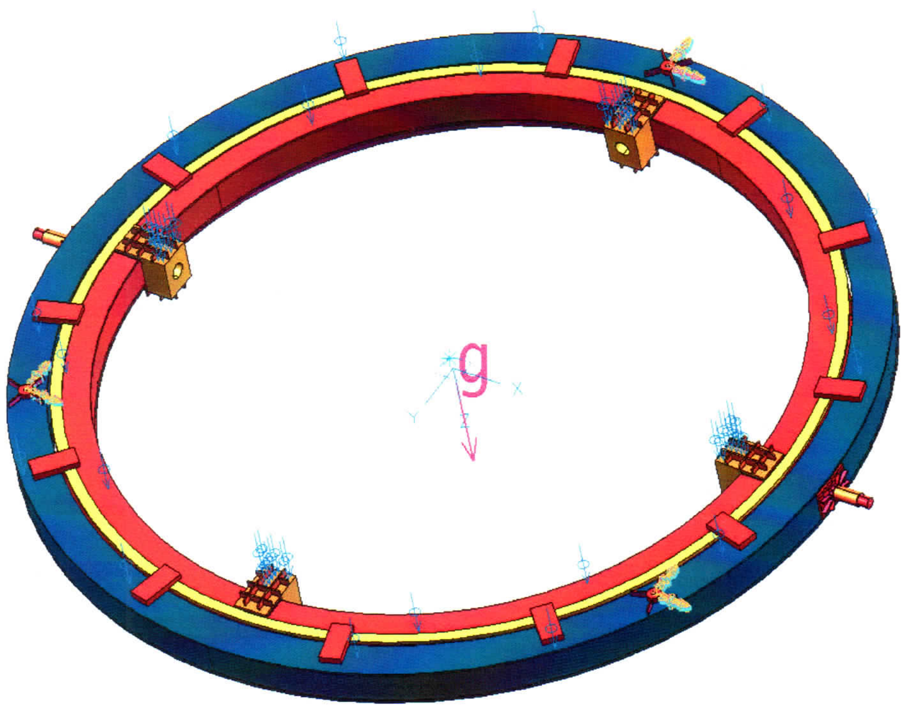



Figure 6. The FEA model of the DECam Rotator Race frames under 3 lifting points case.

The results of the simulating Outer Race frame FEA model under three lifting points case found out that:

Maximum Von Mises stress: 6.96 ksi (See figure 8),

$f_b = f_{yy} = \underline{6.373\ \text{ksi}} < \underline{F_b = 12.00\ \text{ksi}}$ (see figure 9)

$f_v = f_{xz} = \underline{3.372\ \text{ksi}} < \underline{F_v = 12.00\ \text{ksi}}$ (see figure 9)

Total reaction forces of the model: 35,000 lbs which equals the total Applying force to the model (See figure 11 of page 13).

Maximum deflection:

$\boldsymbol{\delta}_{maxFEA}$ = 0.0288" (See figure 8 and figure 10)

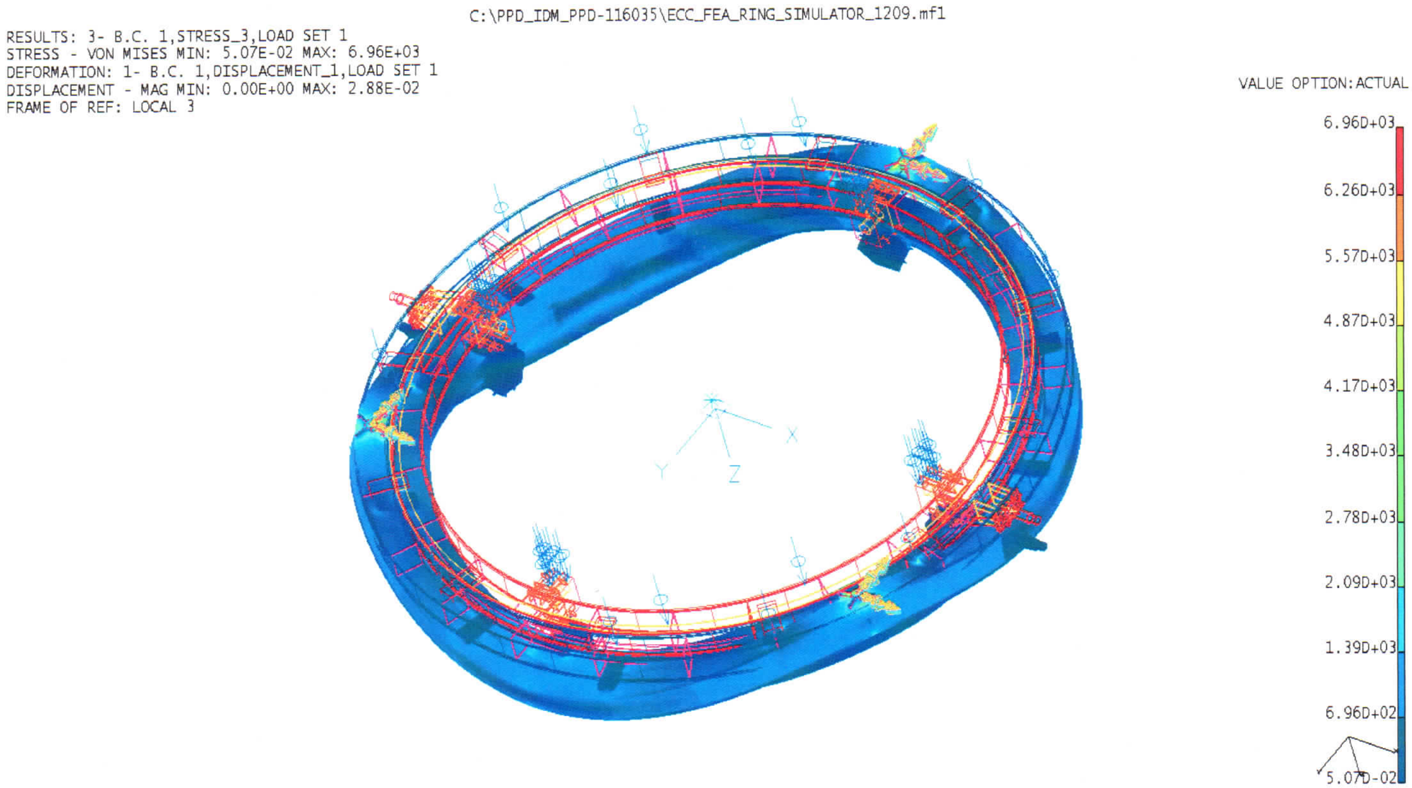



Figure 8, The stress and deflection chart of the Outer Race frame under three lifting points boundary condition.

Page 1

I-DEAS 12 NX Series m4: Simulation 27-Apr-10 13:51:12
C:\PPD_IDM_PPD-116035\ECC_FEA_RING_SIMULATOR_1209.mf1

Group ID : None
Result Set : 3 - B.C. 1,STRESS_3,LOAD SET 1
Report Type : Contour Units : IN
Result Type : STRESS
Frame of Reference: 3 - CS376 Data Component: Y-Component

| | Stress-XX | Stress-XY | Stress-YY | Stress-XZ | Stress-YZ | Stress-ZZ |
|---|---|---|---|---|---|---|
| | 2083 | 43076 | 42896 | 43507 | 209749 | 209752 |
| Maximum | 6.373E+03 | 3.372E+03 | 6.076E+03 | 2.595E+03 | 3.270E+03 | 5.595E+03 |
| | 2137 | 43035 | 174085 | 209611 | 2190 | 1799 |
| Minimum | -2.666E+03 | -3.239E+03 | -3.220E+03 | -2.736E+03 | -2.533E+03 | -2.427E+03 |
| Average | 4.678E+00 | 6.036E-01 | 1.966E+01 | -1.243E-01 | 3.680E+00 | 6.131E+00 |

Figure 9, The stresses of the Outer Race frame under three lifting points B.C.

Page 1

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I-DEAS 12 NX Series m4:    Simulation                    27-Apr-10   13:52:48
C:\PPD_IDM_PPD-116035\ECC_FEA_RING_SIMULATOR_1209.mf1

Group ID           : None
Result Set         : 1 -  B.C. 1,DISPLACEMENT_1,LOAD SET 1
Report Type        : Contour                      Units          : IN
Result Type        : DISPLACEMENT
Frame of Reference: 3 - CS376                     Data Component: Y-Component
```

| | Displa-X | Displa-Y | Displa-Z | Displa-RX | Displa-RY | Displa-RZ |
|---|---|---|---|---|---|---|
| | 5775 | 5317 | 31406 | 1 | 1 | 1 |
| Maximum | 7.642E-03 | 7.308E-03 | 1.226E-03 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| | 5550 | 6863 | 6988 | 1 | 1 | 1 |
| Minimum | -7.847E-03 | -5.237E-03 | -2.747E-02 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| Average | 7.606E-05 | -2.981E-04 | -1.502E-02 | 0.000E+00 | 0.000E+00 | 0.000E+00 |

Figure 10, The displacements of the Outer Race frame under three lifting points B.C.

Page 1

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I-DEAS 12 NX Series m4:    Simulation                    27-Apr-10   13:54:26
C:\PPD_IDM_PPD-116035\ECC_FEA_RING_SIMULATOR_1209.mf1

Group ID           : None
Result Set         : 2 -  B.C. 1,REACTION FORCE_2,LOAD SET 1
Report Type        : Contour                      Units          : IN
Result Type        : REACTION FORCE
Frame of Reference: 3 - CS376                     Data Component: Y-Component
```

| | Reacti-X | Reacti-Y | Reacti-Z | Reacti-RX | Reacti-RY | Reacti-RZ |
|---|---|---|---|---|---|---|
| Total | 3.326E-03 | 1.099E-03 | 3.500E+04 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| | 2141 | 43111 | 43110 | 25 | 25 | 25 |
| Maximum | 1.998E+03 | 2.336E+03 | 3.196E+03 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| | 42966 | 43110 | 42979 | 25 | 25 | 25 |
| Minimum | -2.061E+03 | -2.029E+03 | -1.004E+03 | 0.000E+00 | 0.000E+00 | 0.000E+00 |
| Average | 4.620E-05 | 1.526E-05 | 4.862E+02 | 0.000E+00 | 0.000E+00 | 0.000E+00 |

Figure 11, The reaction forces of the Outer Race frame under three lifting pt. B.C.

## Conclusions:

In order to accurately investigate and study the structural and mechanical behavior of the DECam Simulator Rotator Race frames under the three lifting lug case, it is analyzed and calculated by two approaches:

- Manual mathematically computation method.
- Finite Element Analysis (FEA) method.

It is also very conservatively to choose the smaller value as the "*allowable stress*" from the two applicable codes respectively.

The computed working bending stress and shear stress both are much smaller than the allowable bending stress and allowable shear stress respectively.

The computed maximum deflection between two lifting lugs is about 0.0784" vs. the maximum deflection from FEA is about 0.0288".

The designated welding size of the lifting lug is larger than the computed working welding size (see page 9).

The computed thread pull out force from lifting lug is much larger than the applying load under the current boundary condition.

To this end, the design of the DECam Simulator Rotator Race frames and its lifting lugs are satisfactory subject the lifting condition as it defined from the above boundary condition.

## References:

The detail drawings of the DECam Simulator Rotator:
http://des-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=3600